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A Microsecond Response Pressure Transducer for Blast Wave Measurements

by

D. Pierce

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A MICROSECOND RESPONSE PRESSURE TRANSDUCER FOR BLAST WAVE MEASUREMENTS

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D. Pierce

SUMMARY

The development is described of a pressure transducer which has enabled the pressure on the surface of a wind tunnel model to be measured during the first 30 microseconds following the passage of a blast wave. This has necessitated the elimination of 'ringing' of a piezo-electric transducer over a period during which it normally occurs.

Experiments to develop a transducer for the millisecond range were limited in number but the most promising design of those tested is also described.

Replaces R.A.E. Tech Note No. Aero 2935 - A.R.C. 25819

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ILLUSTRATIONS

1 INTRODUCTION

The simulation of blast waves passing over models suspended in the flow of a supersonic wind tunnel is described in Ref. 1. In that note, the surface pressures produced by the passage of a blast wave over the surface of a hemisphere were deduced from the speed of propagation of the blast wave over the surface, the latter being obtained from a series of spark photographs.

At that time the accuracy of the method could not be assessed in the absence of direct measurements of pressure. The pressure calculated at any point on the surface was that induced immediately after reflection of the blast wave at that point. The vulnerability of aircraft or missile to blast waves depends, however, not only on the increase of pressure behind the reflected wave but also of the pressure-time history and the latter cannot be determined from analysis of the spark photographs.

To further the investigation and to confirm the validity of the method of estimating the peak pressure it became essential to find a way of recording continuously the pressure at the surface of the model during the passage of the blast wave.

The experiments of Ref. 1 show the blast wave to pass over the model in less than 120 microseconds. Because of limitations in the method of simulation of the blast wave, the pressure behind the blast wave front falls rapidly and it was essential, in order to record the peak pressure, to have a critically damped pressure transducer with a rise time of one microsecond.

This note describes experimental work to develop a suitable piezo-electric transducer.

2 PIEZO-ELECTRIC TRANSDUCERS

The principle of the piezo-electric transducer is that, for certain crystalline substances, an electrical charge is developed in the substance proportional to the strain developed when it is compressed. Piezo-electric substances occur naturally e.g. quartz, Rochelle salt, and recently, ceramic substances, barium titanate and lead zirconate have been developed which, although they do not have piezo electric properties in their manufactured state, can, by special polarising techniques, be made to behave piezo-electrically.

The time for a piezo electric crystal to be fully strained depends on the speed of sound in the crystal and its thickness normal to the pressure face. By using thin wafers of crystal, rise times less than one microsecond may be obtained.

There are, however, three main difficulties to be overcome in the design of piezo electric transducers for pressure measurement, e.g.

(1) The crystals respond to acceleration as well as pressure.

(2) For maximum sensitivity the crystals should be compressed in one plane only, i.e. pressure should be prevented from reaching the sides.

(3) It is difficult to prevent the crystal ringing, i.e. preventing the initial tension or compression wave rebounding back and forth through the crystal. An example of this is shown in Fig. 1 which shows a cathode ray oscilloscope record of the output of a commercial quartz gauge subject to a step increase in pressure. Here the transducer continues to ring appreciably for 150 microseconds.

In order to arrive at the design features of the transducers described in this note it is first necessary to examine the effect of a blast wave striking a crystal and the response of a crystal to acceleration.

3 ACOUSTIC MATCHING

3.1 Sudden application of pressure to a crystal

Consider the effect of a step increase of pressure on the face of a crystal.

Let k = speed of sound in the crystal

p = a step increase in pressure

A = cross sectional area of face subject to p

E = Youngs modulus of elasticity of the crystal

ℓ = length of crystal normal to the face subject to p.

Force suddenly applied to the face of the crystal is transmitted through the material at a velocity k, to reach a section x in time $\frac{x}{k}$. At this time the material traversed by the wave front is in uniform motion at a velocity $v \left(= \frac{pk}{E}\right)$ and uniformly strained; the material for $\ell > x$ is still at rest and unstrained. When the wave front reaches the rear face of the crystal the charge developed will be that appropriate to a stationary crystal strained by a load pA.

If the rear face of the crystal is rigidly backed, the velocity, v, cannot be continuous at that face, and a new compression wave is propagated back through the material reducing each section to rest after its passage. At the instant that the wave has reached the front face, the crystal will be at rest but with double the strain and therefore double the charge appropriate to the pressure. To relieve the excess strain a relaxation wave originates at the front face and travels through the crystal, the front face moving forward into the air stream. This relaxation wave in turn is reflected at the rigid back face of the crystal. Successive relaxation and compression waves continue to travel back and forth producing oscillations of the charge, 'ringing', until finally dissipated within the crystal.

For our application it is essential to eliminate this ringing phenomenon. Consider now the condition arising when the rigid backing is replaced by an elastic medium having mechanical properties such that the velocity and force shall be propagated unaltered from the first to the second medium as in the homogeneous case, i.e. on one dimensional arguments

$$\frac{pk}{E} = \frac{p_2 k_2}{E_2}$$
$$pA = p_2 A_2$$

where suffix 2 refers to the backing material

Thus $\frac{AE}{k}$ is the same for both media.

Ideally no change in cross section should occur at the interface as the tension or compression wave can only spread out into an enlarged section at the speed of sound in the material and thus momentary changes in velocity would occur. Thus for area matching $A = A_2$ and $\frac{E}{k} = \frac{E_2}{k_2}$.

Values of E, k, ρ (material density) and $\frac{E}{k}$ for various materials are given in Table 1.

Neubert in Ref. 2 refers briefly to the bar-gauge principle employed and also gives further details of the properties of piezo-electric materials and of other pressure transducers in current use in this field.

3.2 Choice of backing materials

Obviously for perfect matching a backing bar of the same material as the crystal is desirable, its length being chosen so that the time for a wave to travel the length of the bar and return to the crystal, coincides with the desired 'ring' free duration.

In many instances however it is of prime importance to keep the length to a minimum consistent with providing an adequate 'ring' free duration and a backing bar of a material with k much lower than for the crystal may have to be used.

A material with a low k suitable for use with a quartz crystal is lead, its k being $\frac{1}{4}$ that of the crystal. When using barium titanate crystals, backing bars of cadmium can be used, the value of k is however, twice that of lead.

Unfortunately there is no material of low k readily available for matching with a lead zirconate crystal - presumably such a material could be developed. Zinc may be used but as its k is only slightly lower than that of the crystal, it would have little advantage over a backing bar of non-polarised crystal material.

The quartz crystal has a much smaller capacitance than a corresponding barium titanate or lead zirconate crystal so that the latter are to be preferred if long electric cables having relatively high capacitance have to be employed.

Where small transducers are required and pressure measurements of < 1 lb/in^2 are involved it may be necessary to use a lead zirconate crystal in conjunction with a low k material backing bar and accept either cross section mismatch at the interface, with the inevitable momentary change in velocity, or to match cross sections and allow the crystal to change to the new value of v. As a consequence of the change in v either compressive or relaxation wave trains are set up and a degree of ringing within the crystal will result. Since with a transducer of practical size, a reflected wave will eventually return to the crystal bringing it to rest, it is preferable to facilitate this as quickly as possible in such a way that the reflected waves are rapidly damped out.

This method although unacceptable for recording the pressures during the experiments of Ref. 1 is nevertheless useful where millisecond duration recording times are required and where over or underswing of the record during the first 2 or 3 µs can be tolerated. This principle is used in the second of the two transducers described.

4 EFFECT OF ACCELERATION

When pressure transducers are installed for use, the mount, whether this be a wind tunnel model or the walls or end plate of a shock tube, may be subject to pressure changes and therefore of transmitted stress waves and vibration. Unless the transducer can be isolated, which in most cases is impossible, the accelerations of the mount will be transmitted to it.

Consider the effect of a crystal attached to a bar accelerated longitudinally with an acceleration f. The load on the interface due to the mass of the crystal is $\frac{f}{g} A \ell \rho$. The average stress in the crystal is $\frac{f \ell \rho}{2 g}$ and can be assumed equivalent to the stress due to a pressure p_f. For example a crystal of 0.20" thick lead zirconate installed in a mount vibrating longitudinally such that its peak oscillations are ±100g would experience an equivalent oscillating stress of ±2.74 lb/in^2 superposed on the steady pressure independent of its value. Since the sensitivity of a crystal to longitudinal acceleration is proportional to ℓ, then the thinner the crystal the lower will be that proportion of the output signal due to vibration in relation to the total output signal. The thinness of the crystal will only be limited by the degree of amplification available and the ratio of signal output to noise level.

It should also be noted that the mass of any diaphragm, used to exclude pressure from the sides of the crystal, will be added to that of the crystal during acceleration, so that steps should be taken to ensure that its density and thickness are kept to a minimum.

5 TESTING TRANSDUCERS

The transducers have been tested by installing them in the end face of the low pressure section of a closed shock tube and subjecting them to the step increase in pressure produced when the shock wave, formed when the diaphragm between the high and low pressure sections of the shock tube was ruptured, was reflected from the end face.

The signal from the crystal was fed through a high frequency amplifier to a Tektronix oscilloscope. The oscilloscope was set to a suitable sweep speed (normally 20 or 100 µs/cm) and was triggered by a simple switch, mounted on the wall of the tube, operated by the pressure increase behind the shock wave as it passes.

6 A TRANSDUCER OPERATING FROM 0 TO 32 μs

The wind tunnel model on which blast wave pressures were to be recorded consisted of a one inch radius hemisphere. A ring free time of 30 to 40 μs was required and this, together with the limitation of length, necessitated the use of a quartz crystal in conjunction with a matched area lead bar. The design is shown in Fig. 2.

The crystal was soldered to the lead bar with a low melting point solder (Wood's metal). The crystal and lead bar were surrounded by, but insulated from, an outer tube of lead. A thin brass diaphragm connected the top face of the crystal to the outer tube of lead. The outer tube of lead therefore made one electrical connection to the crystal and the inner lead bar the other. The assembly was then slid freely into an outer brass case and secured at the end away from the crystal.

The object of the outer tube of lead is to enable the diaphragm to exclude air pressure from the sides of the crystal without connecting directly to the outer brass case. Thus as the blast wave strikes the diaphragm the compression wave is partly transmitted through the lead tube and partly through the lead bar. These being of the same material, the assembly compresses as a unit within the outer brass case. Stress waves striking the outer brass case can only reach the crystal by being transmitted down the brass case and back through the lead bar and are thereby delayed for some appreciable time.

The length of lead bar chosen should have provided an operating time, free from ringing, of 40 microseconds but records of the response to a step pressure show only 32 microseconds free from ringing. This time corresponds roughly to the time for a wave to travel down the brass tube and back up the lead tube to the crystal. A typical record is shown in Fig. 3.

The sensitivity of the transducer when coupled by 6 feet of electrical cable to the recording equipment was 0.00084 volt/p.s.i.

This transducer was mounted in a hemisphere suspended in the flow of a supersonic wind tunnel and enabled measurements to be taken of the pressure induced on the surface during the passage of a blast wave. The installation of the transducer in the model, and typical pressure records are shown in Fig.4.

7 A PRESSURE TRANSDUCER OPERATING FROM 4 to >1000 MICROSECONDS

The main difficulty in designing this transducer is to find a means of rapidly bringing the crystal to rest without causing extensive ringing. The problem is difficult to solve theoretically and time has permitted only a limited number of experiments to be made. As a result of these the design shown in Fig. 5 shows the most promise.

A 0.020" thick lead zirconate crystal has been used to minimise the effect of acceleration. This was soft soldered to an area matched lead bar which is a tight fit in a resin bonded fabric block. By this means the stress wave travelling down the bar is transmitted to the resin bonded fabric block which appears to have good wave damping characteristics.

The shape of the resin bonded fabric block at the crystal end was designed so that the area subject to direct pressure was small and that the stresses induced in the end cap of the shock tube could not be transmitted directly to the crystal.

One electrical connection to the crystal was made through the lead bar and the other by a small strip of 0.00025" thick copper foil coupling the front face of the crystal to the duralumin end cap. The foil was secured by the transparent adhesive tape used to exclude air from the side of the crystal.

Typical oscilloscope records at sweep speeds of 20 and 100 μ secs per cm Fig. 6 show some 30% overswing during the first 3-4 microseconds. During this time the crystal is being brought to rest. After the first overswing the record remains sensibly level except for a ±5% ripple due, it is considered, to vibration of the end plate of the shock tube. A steady rise in the level of the record occurs from 600 μ secs onwards. This is a function of the shock tube, it being the time at which the contact front between air in the high and low pressure chamber affects the transducer.

The output signal of the transducer was reduced by placing a 4000 pf capacitance in parallel with it; the resulting sensitivity then becoming 0.0042 volts/p.s.i.

It was found that much depends on the method used for fixing the transducer into the end cap. Any fixing which was designed to clamp the main bulk of the block or to support it at the end furthest from the crystal caused adverse effects.

Further experiments are required to find to what extent the length of lead bar and size of block could be reduced and to determine whether improvements can be made in the method of fixing the block into the end cap.

One further problem arises when using a thin crystal to record the pressure in a high Mach flow. This is the temperature rise occurring during the commencement of the flow. The crystal output is sensitive to crystal temperature and it is necessary for the diaphragm to be of sufficient thickness to act as a heat shield during the required recording time. This problem did not arise during the experiments of Ref. 1 where short time intervals were involved, and has not been in evidence during the experiments with the long duration transducer described above.

8 ACKNOWLEDGEMENT

The development of these transducers was spread over some months and during this time the author had many helpful discussions with and assistance from, Mr. D.R. Stevens to whom he is much indebted. Since these experiments were conducted Mr. Stevens has continued research in this field and some further experiments are contained in Ref. 3.

SYMBOLS

k = speed of sound

ρ = density

p = a step increase of pressure

A = cross sectional area of crystal subject to p

E = Young's modulus of elasticity

ℓ = length of crystal normal to the face subject to p

t = time commencing when a step in pressure p first reaches crystal

v = velocity of any section of crystal

f = acceleration

μ = microseconds = 1×10^{-6} seconds

Suffix 2 refers to backing bar

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No.	Author	Title etc.
1	Pierce, D.	Simulation of blast waves in a supersonic wind tunnel. ARC. 21891 January, 1960
2	Neubert, H.K.P.	Instrument transducers. Clarendon Press, 1963
3	Stevens, D.R.	The evaluation of some commercial and development pressure gauges in a laboratory type shock tube with a view to their suitability for use in shock tunnels. ARC. C.P. 677 March, 1962

TABLE 1

Characteristics of materials

Material	ρ lb/in^3	E lb/in^2	k ft/sec	$\frac{E}{12k}$ $\frac{lb\ sec^2}{in^3}$
Quartz	0.094	9.5×10^6	16,500	480
Barium titanate	0.202	13.6×10^6	13,500	841
Lead zirconate	0.274	12.0×10^6	10,800	926
Steel	0.28	28×10^6	16,400	1425
Brass	0.31	14.3×10^6	11,100	1075
Copper	0.318	15.5×10^6	11,500	1125
Aluminium	0.092	9.8×10^6	16,900	484
Lead	0.41	2.5×10^6	4,000	521
Zinc	0.258	14.0×10^6	12,100	964
Tin	0.263	6.4×10^6	8,100	658
Cadmium	0.310	8×10^6	8,300	804
Bismuth	0.354	4.6×10^6	5,900	650
Glass	0.094	8×10^6	15,100	441
Wood's metal	0.35	4.4×10^6	5,800	632
Perspex	0.043	0.45×10^6	5,300	708
Araldite	0.045	0.5×10^6	5,400	772

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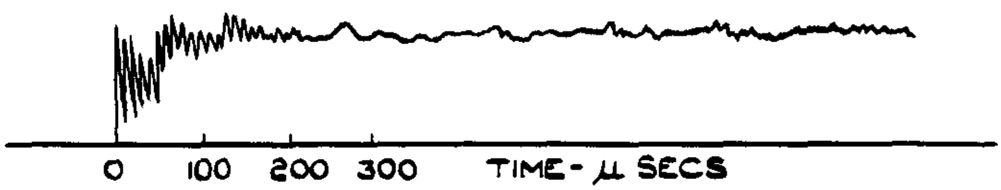


FIG. I. RESPONSE OF COMMERCIAL TRANSDUCER TO A STEP INCREASE OF PRESSURE.
(TRACED FROM ORIGINAL FOR CLARITY.)

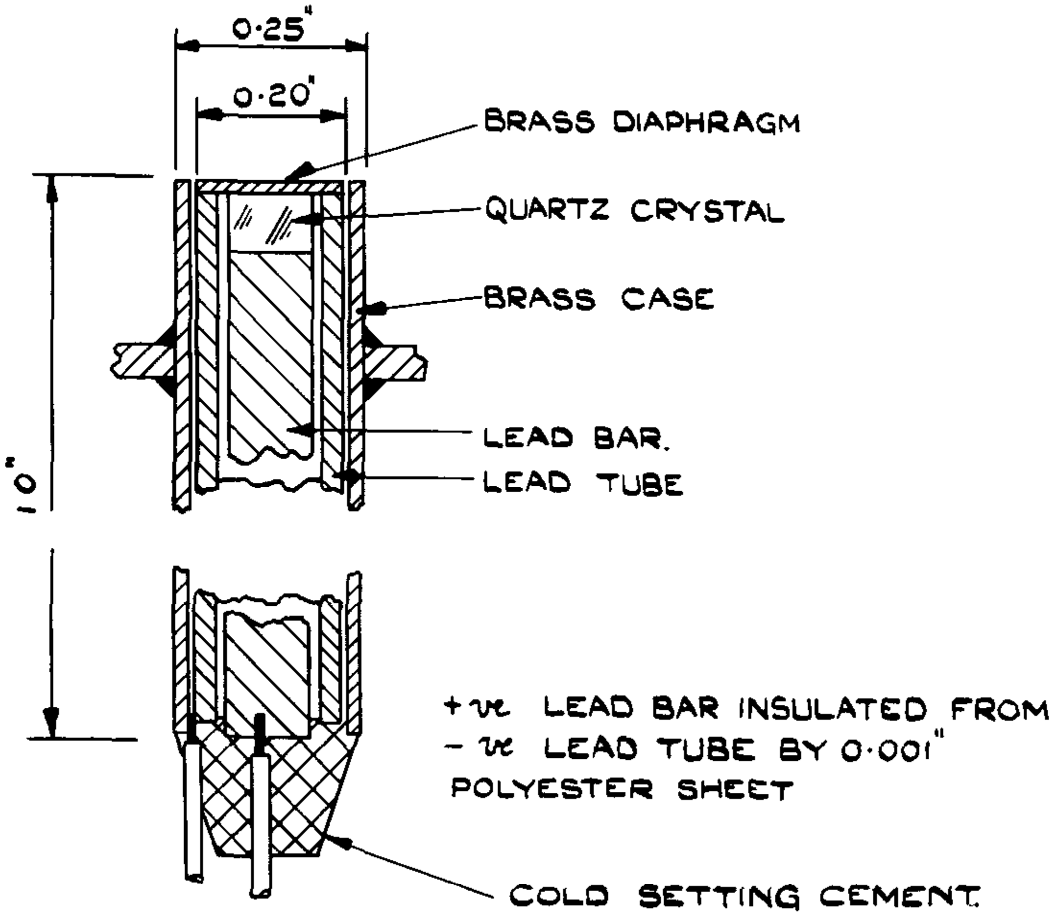


FIG. 2. 32 μS TRANSDUCER DESIGN.

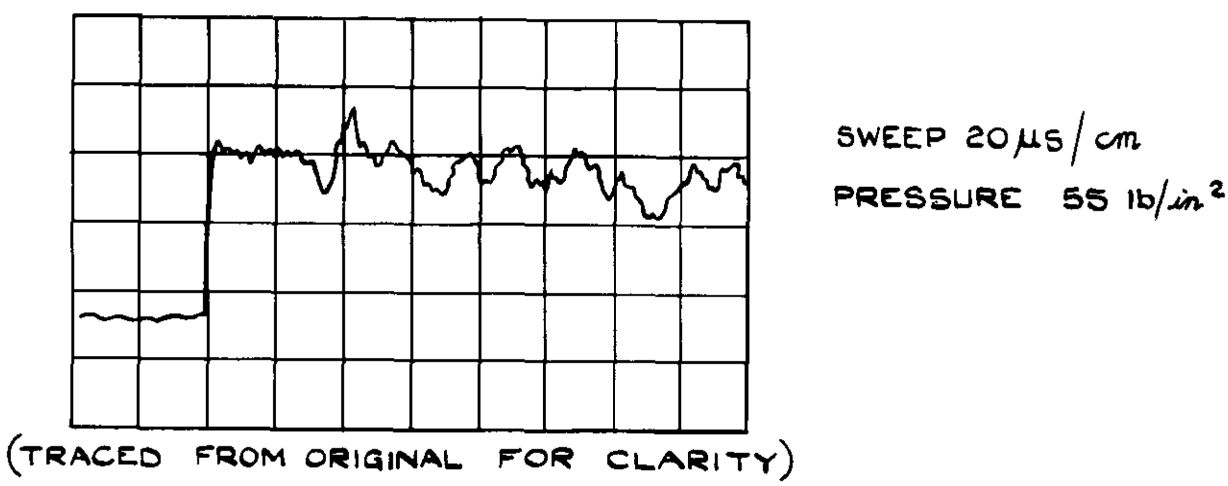


FIG. 3. RESPONSE OF 32 μS TRANSDUCER.

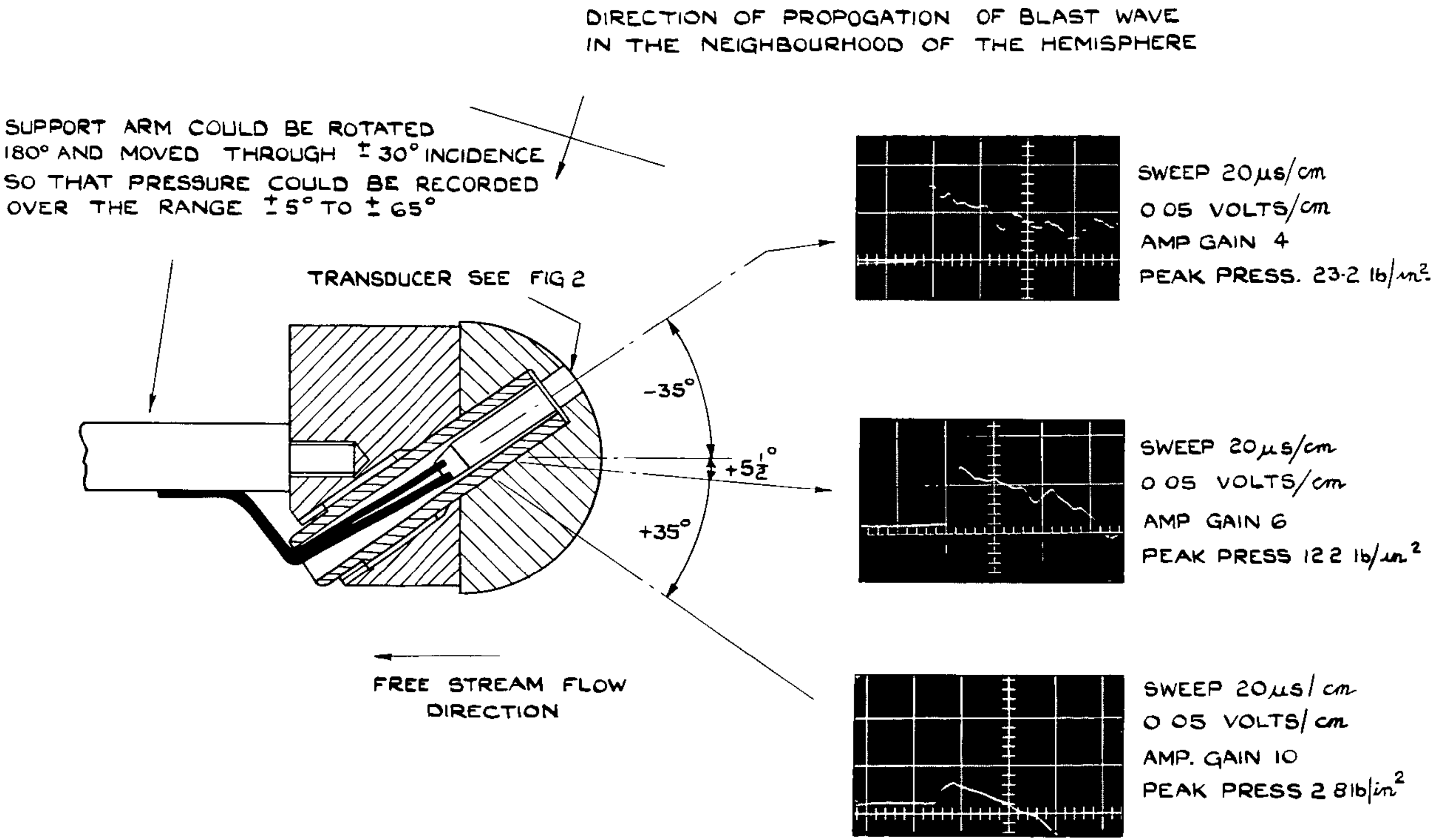
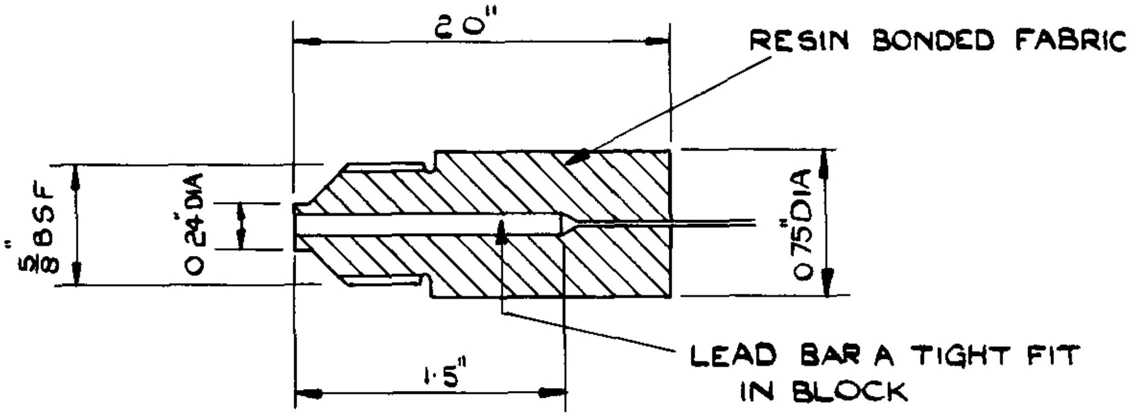
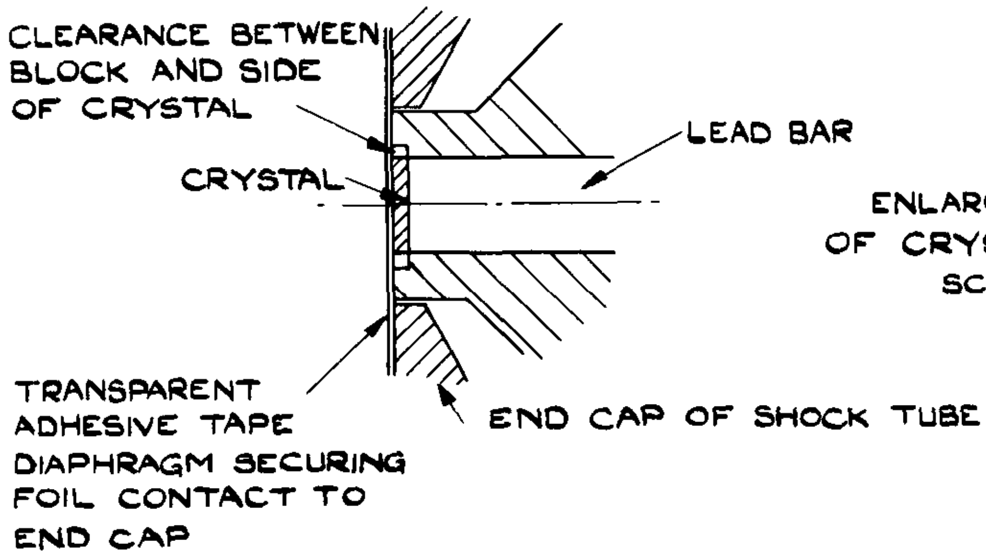


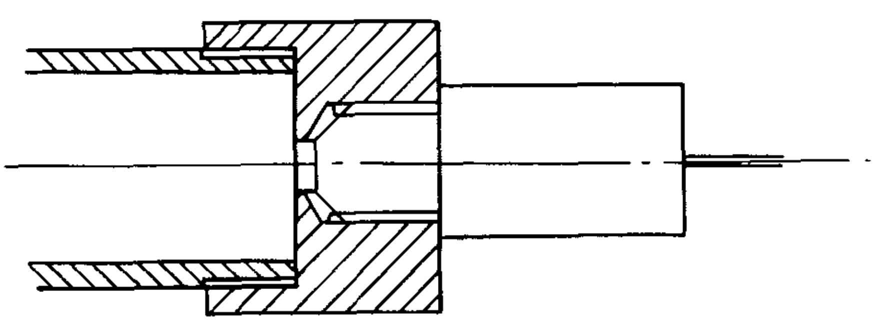
FIG. 4. INSTALLATION OF TRANSDUCER IN THE WIND-TUNNEL MODEL WITH DIAGRAMS OF ITS RESPONSE TO BLAST WAVES.



TRANSDUCER

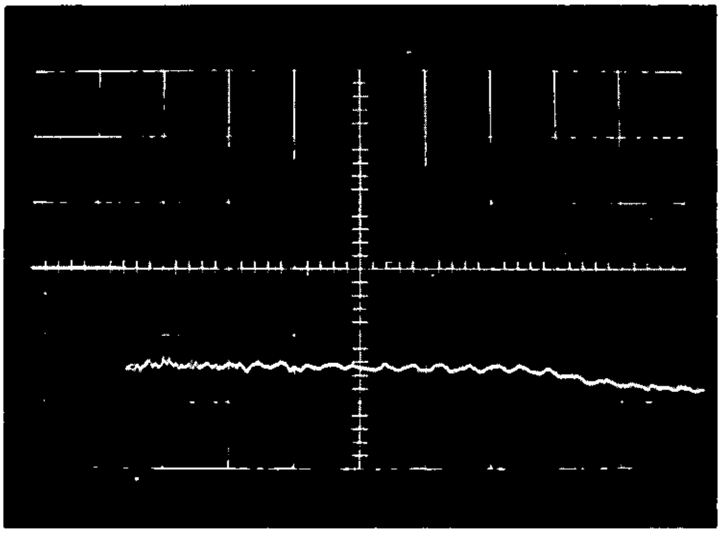


ENLARGED VIEW
OF CRYSTAL MOUNTING
SCALE 4/1

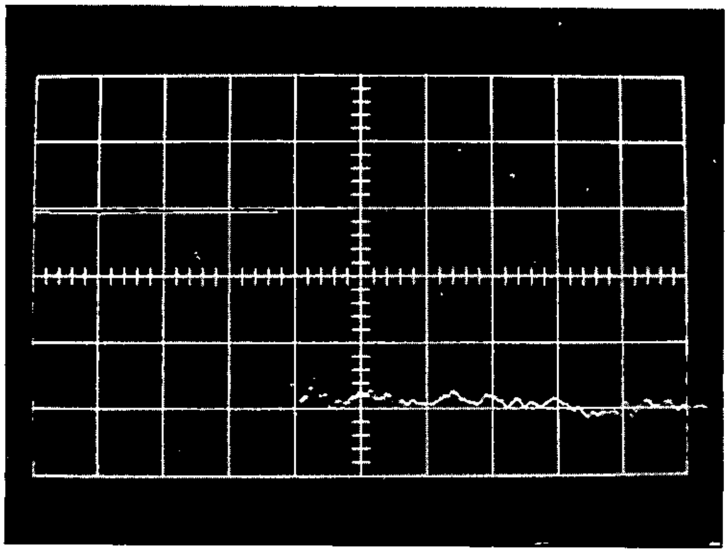


TRANSDUCER MOUNTED IN END CAP OF SHOCK TUBE.

FIG. 5. MILLISECOND RECORDING TIME TRANSDUCER.



Sweep 100 μs/cm
pressure 62 lb/in^2
0.2 volts/cm



Sweep 20 μs/cm
pressure 33 lb/in^2
0.05 volts/cm

FIG.6. RESPONSE OF MILLISECOND TRANSDUCER

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